An Innovative Approach to Satellite Technology

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Introduction: Innovation and rapid prototyping using advanced technologies are the hallmarks of new initiatives coming from the USAF Research Laboratory's Office of Scientific Research (AFOSR).

University Nanosatellite Progrram. AFOSR, in conjunction with DARPA, is sponsoring ten universities, formed into small teams and challenged with paving the way to novel space capabilities. The satellites leverage innovative thinking within our universities, leading to flight experiments of state-of-the-art technologies and advanced mission concepts. Experiments range from micro-propulsion to formation flying. These miniaturized satellites will be prototyped and launched. We describe the philosophy, approach, and results to date of the program.

TechSat21 Program. Recent progress in the miniaturization of key satellite technologies enables innovative solutions for space missions. AFOSR, in conjunction with AFRL's Space Vehicles Directorate, has developed the TechSat 21 program. This low-cost, lightweight cluster of cooperating microsatellites may eventually replace today's heavy and more expensive systems. Each microsatellite will communicate with other members of the cluster to share information and mission functions, thus comprising a "virtual" satellite. TechSat 21 offers the flexibility to incorporate cutting edge technology in a reconfigurable constellation. This unusual approach offers multi-mission capability as well as a reduced life cycle cost. It is envisioned that new technology may be inserted by replacing members of the cluster with enhanced versions. Research and technology investments include sparse aperture sensing, local communications in space and microsatellite bus technologies. The investment in innovative basic research areas to make TechSat 21 a viable alternative as well as the overall program approach will be covered. Many of the techniques and technologies being demonstrated in the University Satellite program have application to the TechSat21 program.

University Nanosatellite Program Summary: The Air Force Office of Scientific Research (AFOSR) and the Defense Advanced Research Projects Agency (DARPA) are jointly issuing research grants centered on the design and flight experiments of nanosatellites. (Satellites sized 1 - 10 kg). These grants over two years have been awarded for universities to design, assemble, and conduct on-orbit experiments for these satellites. Universities are to pursue creative low-cost space experiments to explore the military usefulness of nanosatellites in such areas as formation flying, enhanced communications, miniaturized sensors, attitude control, and maneuvering.

The Air Force Research Laboratory is developing a deployment structure, integrating the nanosatellites, securing a launch, and providing such advanced microsatellite hardware as high efficiency solar cells and micropropulsion. NASA Goddard has also teamed with the universities to provide funding to demonstrate such formation flying technologies as advanced crosslink communication and navigation hardware and flight control algorithms. Numerous industry partners are also supporting the universities with hardware and providing design and testing services. Information on the program and presentations from the kick-off meeting can be seen at the website, http://www.nanosat.usu.edu/.

The universities selected for the program are: Arizona State University, University of Colorado at Boulder, and New Mexico State University (Three Corner Sat); Stanford University and Santa Clara University (Emerald); Boston University (Constellation Pathfinder); Carnegie Mellon University (Solar Blade Nanosat); Utah State University (USUSat); Virginia Polytechnic Institute and State University (VTISMM); University of Washington (UW Nanosat). Descriptions of their satellite programs follow.

Three Corner Sat Constellation (3$\measuredangle$Sat): This project is a joint effort among Arizona State University (ASU), University of Colorado at Boulder (CU), and New Mexico State University (NMSU). Aptly named Three Corner Sat (3$\measuredangle$Sat), the proposed constellation of three identical nanosatellites will demonstrate stereo imaging, formation flying/cellular-phone communications, and innovative command and data handling. In addition, each University in the 3$\measuredangle$Sat constellation has the opportunity to fly an individual unique payload should it desire.

The primary science objective of the 3$\measuredangle$Sat constellation is to stereo image small (< 100 meter), highly dynamic (< 1 minute) scenes including deep convective towers, atmospheric waves, and sand/dust storms. These stereo images will enable the computation of range to within 100 meters giving accurate data regarding the shape, thickness and height of the observed phenomena.

Stereo imaging from space has several advantages over conventional imaging, the most obvious being the ability to derive range data. This range data can be substantially more accurate than range data acquired by other more usual means and also can cover a much

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greater area. Stereo imaging involves correspondence matching between an image pair and calculation of the resulting disparity. From the disparity, triangulation can be used to determine range data, and three-dimensional images and depth maps can be created. Accurate depth maps with range resolutions of about 100 meters enable the study of relatively small-scale, short-lived atmospheric events such as cumulus-cloud towers.

To accomplish the science objectives, a "virtual formation" is proposed as part of this program. The virtual formation is a cooperative effort between satellites operating as a network where targeting and data acquisition are accomplished and results transmitted to the ground segment and to the other satellites via communications links without the need for strict physical proximity of the satellites. In this mode, the communications links carry the command and control data necessary to accomplish the mission regardless of the physical location of the satellites. For the mission to be accomplished, the locations of the satellites will need to be "in range" and mutually known in order for each to support its portion of the mission, but physical proximity is not a requirement for the formation network.

For stereo imaging, a nominal spacing of tens of kilometers between the satellites is required. With a controlled deployment to achieve this initial spacing, the satellites will remain within range for the suggested four-month lifetime of the mission. Therefore propulsive capability is not needed.

LEO satellites utilizing cellular telephone constellations is a new concept but one in which there is considerable interest in the government and private-sector space communities. This natural extension to the use of ground-based systems will be explored not only to demonstrate the utility of this mode of communications but also to act as an experiment to characterize the constellation itself and the limits on the operations. A technology goal of 3⅄Sat is to perform the first steps in this characterization.

The 3⅄Sat constellation will consist of three satellites flying in a linear follow-formation with relatively constant separation from each other. The separation distance selected is based on altitude and camera field of view (FOV), with final determination based on the chosen launch vehicle. The mounting configuration within the launch vehicle will depend upon the launch vehicle and other satellites selected. The satellite will use gravity-gradient (GG) forces for stabilization with +/- 5 degrees pointing accuracy.

All satellites will be identical, except for a standard payload envelope where each university will have the option to fly its own unique experiment after the primary science objective has been met. The spacecraft structure will be low-cost and reliable. The exterior envelope of the structure is a six-sided disk structure consisting of tubular supports and machined end caps to hold the bulk of the loading (Figure 1). The design will feature a number of modular, removable trays, allowing for on-the-spot modifications without extra machining or irreversible processes.

EMERALD: Stanford University and Santa Clara University are jointly developing EMERALD, a low SSDL (Space Systems Development Lab) and Santa Clara University's SCREEM (Santa Clara Remote Extreme Environment Mechanisms Laboratory) are working as a unified team to develop, construct, test and eventually operate the EMERALD spacecraft. The formation flying experiments will be coordinated through Stanford's ARL (Aerospace Robotics Lab).

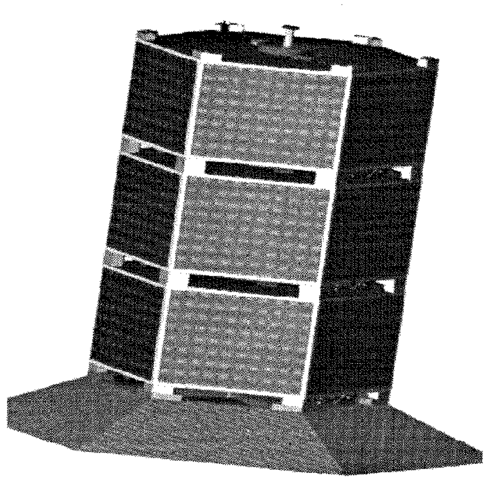


Figure 1. Spacecraft Overview

The Emerald Mission is divided into three distinct stages, that progress from a simple single satellite to two free flying satellites in a coarse formation. Using a building block experimental strategy, the research payloads first will be characterized in isolation. Then, they will be coordinated and combined to permit simple demonstrations of fundamental formation flying control functions such as relative position determination and position control.

At release, the two spacecraft will be stacked together and will travel as a single object. This will allow initial checkout, calibration, and some limited experimentation.

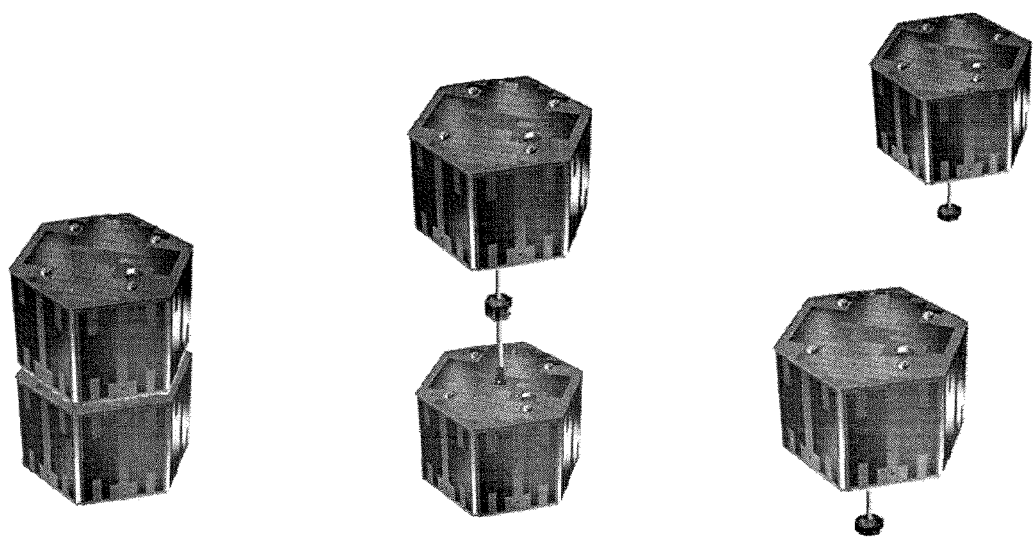
During the second stage of operation, the satellites will separate and a simple tether or flexible boom will uncoil, linking the two vehicles. This tethered stage will allow full formation flying experimentation including on-orbit relative position determination and simple closed loop relative position control using the drag panels and micro-thrusters.

During the final stage of operation, the tether will be cut in order to permit true two-body formation flying for a limited period of time. The tether will have a simple sub-satellite at its midpoint. Upon ground command, the two halves of the sub-satellite will separate. Each satellite will retain half of the tether and half of the sub-satellite, providing very rough gravity gradient stabilization.

The two EMERALD spacecraft will demonstrate several critical technologies for future formation flying missions: GPS-based positioning, Inter-satellite communication, advanced colloid micro-thrusters, and passive position control devices. In addition to these mission critical payloads, Emerald will support a couple of auxiliary payloads: VLF receivers and the MicroElectronics Radiation In-flight Testbed.

These experiments will be built into a 12-inch tall, 18-inch diameter hexagonal bus adapted from heritage designs at SSDL. The structure employs a modular, stackable tray structure made of aluminum honeycomb. Inside, command and data handling is provided by a Motorola 68332-based processor built into a student developed radiation tolerant architecture. Ground communication will be handled by a 9.6 kbs packet communications system. The heritage power system consists of body mounted Silicon cell solar panels and a single Ni-Cad battery. This system will provide 7 Watts of average power to components via a 5V regulated bus.

Constellation Pathfinder: This program between Boston University and Draper Lab will demonstrate fabricate and launch one to three, <1 kg satellites that are capable of collecting and returning quality scientific and engineering data for one to four or more months. The particular satellite to be used is based on one developed over the past two years through a NASA-supported study called the Magnetospheric Mapping Mission (MMM) at Boston University. That study objective has been to assess the feasibility of placing hundreds of satellites equipped with magnetometers, into orbits extending into the tail of the magnetosphere, thereby obtaining a much more detailed three-dimensional picture of dynamic phenomena in geospace than has been possible previously. The Constellation Pathfinder proposal will take the first pathfinding step toward such an ultimate implementation. A proposed simplification of the current conceptual design is that the launch mechanism is provided by the Shuttle

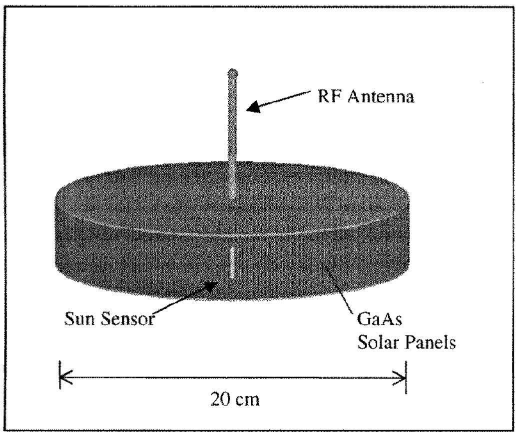


(a) Phase I:Initial Deployment *(b) Phase II: Tethered Operations* *(c) Phase III Separated Operations.*

Figure 2: *Mission Sequence*

Hitchhiker. The magnetometer will be measuring larger (and therefore easier to measure) fields in the Earth's ionosphere, the lower altitude reduces RF communication requirements as does relaxation of the required data transmission rate, and the natural radiation environment will be much lower. The hardware demonstration of building and flying such a satellite, or small suite of satellites, will provide a proof of principle that will be helpful in many scientific and strategic applications where a fleet of coordinated small satellites is required. Satellite-to-satellite communication may also be accomplished.

The nanosatellite configuration is shown below. The outer cylindrical surface consists of power-providing GaAs solar cells. The RF antenna is along the axis of the cylinder. Satellite spin will maintain the orientation of both the antenna and the solar cells within 10 or 20 degrees of the ecliptic plane assuming that one can select the shuttle orientation at the time of release to be in this range. The satellite electronics including batteries will be concentrated in the center. The magnetometer location is chosen to minimize contamination by spacecraft magnetic fields and will be located within the cylindrical volume. The sun sensor looks radially outward and will be used to determine the phase of rotation. Additionally in conjunction with the magnetometer it will determine the direction of the spin axis.



Solar Blade Heliogyro Nanosatellite: Solar sail concepts have existed for decades, but their implementation has been elusive, and none have flown. The primary difficulty has been the need for great surface area relative to mass. Traditional spacecraft designs with hundreds of kilograms of mass led to kilometers of sail dimensions, which were impossible to rationalize, build, and fly. Nanosat technology drastically reduces mass and makes heliogyro design eminently practical and flyable.

Carnegie Mellon will develop and fly the first solar sail, a spacecraft which utilizes solar radiation pressure as its only means of propulsion and attitude control. The solar pressure will enable altitude changes, attitude precession, spin rate changes and orbital position changes.

The Solar Blade Heliogyro Nanosatellite has the appearance of a Dutch windmill and employs control akin to a helicopter. Four solar reflecting blades mount radially from a central spacecraft bus and actuate along their radial axis. The satellite uses collective and cyclic pitch of these solar blades relative to the sun's rays to control its attitude and thrust. The spacecraft weighs less than 5 kilograms, and, when stowed, is a package approximately the size of a fire extinguisher.

This satellite experiment includes attitude precession, spin rate management, and orbital adjustments, after which it will spiral out past the orbit of the moon. For the Solar Blade Nanosat, plane change maneuvers will be most efficient when the sun is furthest out of the orbit plane. This increases the magnitude of the orbit-normal component of force that can be used for the plane change maneuver. Plane change maneuvers can also be conducted if the sun lies in the orbit plane by orienting the solar blades at an angle relative to the orbit plane, optimally 45°. Unlike eccentricity changes, which can be implemented throughout the orbit using a single solar blade orientation, plane change maneuvers must change polarity on opposite ends of the axis of plane rotation. This is not possible unless the sun is in the plane of the orbit (the solar blades cannot produce a positive orbit normal force if the sun is above the orbit plane). Therefore, in most situations, plane change maneuvers will be conducted over an orbital arc on one side of the orbit near the axis of desired orbit rotation. In addition to attitude and orbital maneuvering, the ultra-light spacecraft will communicate with the Earth, uplinking commands and relaying orbital and attitude information to ground stations.

Solar cells embedded on the flanges of the C-beam frame provide up to 28 Watts of power. The spacecraft computer, communication system, and station-keeping sensors at the center of the square connect to the frame through thin lenticular beams. Wiring between the solar cells and the other subsystems consists of thin-film flexible printed circuits.

USUSat: This project will be built at Utah State University supported by faculty, professional engineers, and through the use of existing space engineering curriculum in both the Mechanical and Aerospace Department and the Electrical and Computer Engineering Department.

The USUSat program has four technology goals or science objectives: 1) Develop a 3-axis attitude controlled nanosatellite. The limited power available on a nanosatellite poses a challenge for 3-axis attitude control. This challenge will be met with an all magnetic torquer system where permanent magnets on stepper motors are used instead of traditional torquer coils. The attitude determination will be achieved by a combination of Earth horizon and sun sensors, giving three axis control to approximately two to three degrees; 2) Demonstrate that coarse orbital control maneuvers can be achieved by using the spacecraft's attitude to control the aerodynamic force vector on the spacecraft. In effect, the attitude control system acts to modulate the aerodynamic drag to change orbital position; 3) Modulate the aerodynamic drag to fly as a formation with the nanosatellites being developed by University of Washington and Virginia Tech. The primary objective is to demonstrate that drag modulation can be used for relative in-track station keeping; 4) Make the first multi-satellite electron density measurements of the Earth's ionosphere using USUSat and the nanosatellites being developed by University of Washington and Virginia Tech. Each of the nanosatellites will carry a probe for measuring electron density built or designed by Utah State University. The multi point measurements of a constellation provides additional information required to answer questions about ionospheric density disturbances that can not be addressed by single satellite measurements.

The entire spacecraft will be covered with solar cells, with the exception of the areas designated for the possible plasma thruster systems. This design requires no deployable structures. The combined sun and horizon sensors will extend from the body in small pods, while the antenna is expanded to be either a 1/8th dipole or a set of patch antennas. The structure is hexagonal with an approximate width of 18 inches and height of 5 inches. This configuration can be modified as needed to meet the specific launch environment conditions. The power subsystem will be a typical solar cell/battery design. Unused solar cells from a GPS satellite solar panel will be individually tested and reassembled into the solar panels for USUSat. The power regulation electronics will make use of components developed commercially for portable laptop computers. The telemetry system will be a low-cost S-Band system developed at USU and includes all components from antennas to encoders. A 14-foot tracking antenna at USU will be used for the ground control station.

University of Washington Nanosatellite: The University of Washington will design, develop, and operate a nanosatellite, focusing on mission objectives that would benefit TechSat21 and future Air Force missions. The UW has partnerships established with Utah State University (design, science, research), Primex Aerospace Corporation (design, coop students), Honeywell Space Systems (design, research, coop students).

The program objectives and descriptions for the UW nanosatellite are as follows:

1) Basic research mission of investigating global ionospheric effects which affect the performance of space based radars, and other distributed satellite measurements.

The science objective is to understand ionospheric density structures that can impose large amplitude and phase fluctuations on radio waves passing through the ionosphere. This study contributes to TechSat21 basic research mission of investigating global ionospheric effects that affect performance of space based radars, as well as broader Air Force interests in navigation and communication links.

The satellite instruments (most likely plasma frequency probes) will determine the global distribution of plasma structure in both the quiet and disturbed ionosphere. The UW will fly the same instrument as Utah State. These instruments will be extremely useful for a number of interesting targets:

a) F region irregularities, especially at the equator, but also at mid latitudes. Several probes with km-scale spacing permit a superb sequence of "space-like" traces.

b) With high latitude field aligned structures, the satellites will on occasion pass through auroral arcs. The formation of satellites should provide superb space-like snap shots of density through the arcs.

In the latter case, the UW will operate a 100 MHz radar to detect these irregularities from the ground, and permit simultaneous calibration of the transmitter, as well as fluctuations in phase associated with irregularities associated with hundred meter structures on an integrated path.

2) Formation flying and local communication in a constellation, including upgrade of a nanosatellite into a constellation already flying in formation.

The need for small, low cost satellites that can fly in formation and perform collaborative mission objectives is becoming increasingly important. Future applications include surveillance (Space Based Radar), earth science and mapping (ionosphere and magnetosphere), astrophysics (stellar interferometry, and communications (laser). In addition, formation flying, on-orbit maintenance and communications, and other distributed satellite capability are enabling technologies to be demonstrated in TechSat21. The UW will use the USU nanosatellite to examine local communications between satellites, leader-follower demonstrations, and decommission and/or upgrade demonstration.

3) Baseline potential new technologies including microthrusters, miniaturized solar arrays, a thin-film polymer modulator for an optical communication link, or satellite autonomy.

Two versions of microthrusters are currently in conceptual phases. Primex is researching a number of options in the micro-Newton range, and will fly a prototype if available during the design of the UW nanosatellite. These include micro pulsed plasma thrusters, and micro-hydrazine thrusters. The launch choice will obviously affect this decision, as will the maturity of the technology. The UW and Primex are committed, however, to flying a prototype microthruster.

Dr. Larry Dalton of the UW is exploring the development of thin-film polymer modulators for optical communication links (good up to at least 200 GHz). Polymer materials have become increasingly important for electro-optic devices because of their low dispersion and fast electronic response. These modulators are unique in that they are low weight (plastic), low power (less than 1 W), and capable of beam steering and forming. The technology will not be used for the communications subsystem, but simply as a low cost technology demonstration between nanosatellites.

VTISMM: The Virginia Tech Ionospheric Scintillation Measurement Mission (VTISMM) is a multiple spacecraft design, build, and fly space project. It comprises two small satellites flying in close proximity, using a GPS receiver for position determination, microsensors for attitude determination, interlink communications for data transmission and relative position determination, and GlobalStar for telemetry, tracking, and commanding. Additionally, VTISMM uses an amateur space-to-ground link as an alternative to the GlobalStar communications link; this space-to-ground link takes advantage of Virginia Tech's Satellite Tracking Laboratory, which is used in teaching undergraduate astrodynamics and space systems courses. The VTISMM science mission focuses on collecting and analyzing GPS data to characterize ionospheric scintillation effects on the communications signals.

The VTISMM system will be designed, built, and operated by undergraduate students in Aerospace Engineering and Electrical Engineering, using existing facilities. Undergraduates are participating in the project through capstone design courses and special project technical electives supervised by the principal investigators. The principal investigators have active research programs involving key aspects of the VTISMM concept, including flight dynamics, space system design, satellite communications, computer systems, power systems, and the effects of ionospheric irregularities on communications signals. These research projects are funded by the National Science Foundation, NASA, AFOSR, and industry.

The VTISMM system is in the preliminary design phase, with a team of juniors and seniors from aerospace, electrical, and computer engineering working towards a formal preliminary design review in May 1999. The two satellites, called Sulu and Uhura, have a common bus design for simplicity, but have different payloads. Sulu (the navigator) has a GPS receiver for its payload, and Uhura (the communicator) has a GlobalStar communications set for its payload. Both spacecraft buses include a flight computer, intersatellite communications, and attitude sensors. One (possibly both) spacecraft also includes an amateur band communications system as an alternative to the GlobalStar communications link. This link communicates with the existing satellite tracking station at Virginia Tech, using amateur satellite frequencies, or other frequencies as appropriate. Uhura also includes a small digital camera.

TechSat 21 Project Description: TechSat-21 consists of a cluster of small satellites that orbit in formation to create a distributed aperture. This cluster of satellites forms a "virtual satellite" which performs radar functions that typically require a large heavy antenna. The distributed aperture provides high angular resolution that offsets the disadvantage of large clutter spread arising from each satellite's small aperture. By providing highly accurate angular information, the ambiguity in Doppler between "stationary" ground clutter and moving targets can be resolved. The additional angular resolution is enabling for multi-mission modes of operation, dramatically increasing military value and utility. Furthermore, having many satellites in the cluster offsets the small signal to noise ratio of each satellite. This approach can be cost effective due to economies of scale (large production runs of small satellites), the adaptability of the system, the capability to reduce launch costs by using smaller launchers and rides of opportunity (piggyback other missions), and its inherent robustness. This approach leverages space industry investments in large constellations of small communications satellites (e.g. Iridium, Teledesic).

TechSat -21 is inherently robust to on-orbit failures since the loss of a single satellite in a cluster will cause only a small decrease in performance. It enables line replaceable unit maintenance for the virtual satellite by replacing/adding satellites to the cluster. Constellation performance upgrades (similar to aircraft block changes) are possible by adding new satellites to the cluster with better individual performance to improve the virtual satellite performance.

A combined AFOSR basic research and AFRL applied research program is underway to develop the scientific and technology basis for this concept. Initial analysis has shown the technical and scientific feasibility. The follow-on research program will refine and expand the scientific and technical knowledge base to enable demonstration of this concept.

TechSat -21 is a revolutionary approach to space based surveillance. It replaces a single large (and very expensive) satellite with a cluster of smaller satellites flying in formation. However, since each satellite has sufficient autonomy and collaborates effectively with the other satellites in the cluster, the cluster appears to be a single satellite or a virtual satellite from the point of view of the operator or user. Thus, the infrastructure for command and control of the TechSat -21 constellation is no different from an equivalent constellation of larger satellites.

A summary of the technologies of importance to TechSat -21 follows. AFRL/VS and AFOSR are investing in research projects in most of the less mature areas.

1) Antenna: Two-dimensional steerable (60^0 each axis) X-band phased array antenna, less than 4 kg/m^2 (current systems are typically 20 kg/m^2). Moderate bandwidth requirements of approximately 300 MHz.

2) Thin film solar array: Lightweight thin film photovoltaics that can yield solar arrays of greater than 200 W/kg and less than $100/W. This improves weight and cost by a factor of four over conventional planar,

crystalline photovoltaic systems. Requires advances in thin film cell efficiency from approximately 7% to 14% (air mass zero).

3) DC/DC converters: 90% efficiency at 500 W/kg.

4) Parallel computers: Low mass, low power, high speed digital signal processors for parallel computation application. Need greater than 200 MFLOPs/W and greater than 5000 MFLOPs/kg. This represents an order of magnitude improvement over current technology.

5) Distributed radar phenomenology: Algorithms and techniques for processing sparse aperture data to produce radar images and detect moving targets are needed. STAP techniques appear useable, but require significant engineering to adapt to sparse aperture systems and to implement efficiently in a parallel environment. Other more optimal techniques from interferometry or information theory may improve performance or reduce the processing and data storage requirements.

6) Ionospheric effects: The spatial inhomogeneity of the ionosphere on the scale of this large aperture may affect radar operation. Models and measurements of the ionospheric structure and predictive tools for their effects need to be developed.

7) Micro pulsed plasma thrusters: Small impulse bit propulsion is required to maintain the geometry of the satellite cluster. The most promising propulsion technology is pulsed plasma thrusters because the fuel is solid and non-volatile (easing integration of the propulsion system since there are no fuel lines, valves, or tanks), it has good specific impulse, and it can be throttled. Miniature thruster devices are required to reduce weight by taking advantage of the small impulse requirements.

8) Multi-functional structure: Highly integrated electronics packaging and mass-producible lightweight interconnects and harnesses are required to achieve significant cost and weight reductions. Techniques for providing adequate thermal dissipation and mechanical support are required. The radiation shielding lost by eliminating massive boxes, harnesses, and connectors must be supplemented by integrating spot shielding, radiation shielding composite structures, and increased radiation hardness of parts.

9) Lightweight star sensor: Low cost, lightweight (less than 1 kg), moderate accuracy star sensors are required. Pointing accuracy of 0.02^0 and a field of view of at least 30^0 are required. Autonomous star acquisition is desired to minimize additional sensor requirements.

10) Inflatable boom: Highly packageable, deployable structures will greatly reduce the stowed volume of the satellite, allowing more effective packaging on existing launch vehicles. Lightweight booms capable of over 200:1 compaction ratios with deployed stiffness of greater than 1 Hz are needed to deploy the solar arrays and gravity gradient boom.

11) Lithium ion battery: High energy density and low cost are the key technology drivers. Specific energy densities of over 100 Whr/kg for 6 to 8 Amp-hr cells are required. Desired depth of discharge for 15 year LEO cycle life is 30%. Batteries that allow production in arbitrary shapes and form factors are desirable to provide compact satellite geometries.

12) Variable emissivity coatings: Electrochromic materials are required to permit voltage modulated control of infrared emissivity or solar absorptivity (from 0.2 to 0.8) in the 3 to 25 micrometer spectral band. Low power actuation of less than 0.2 W/m^2 at less than 5 VDC for full switching. Long life in a space environment is required, including multi-level stability, insensitivity to static charge, and greater than 15 year life.

13) Formation flying control: Techniques are required for autonomous and collaborative control of the satellite cluster for the life of the mission. Satellites must maintain a specified geometry within 10s of meters over separations of 100s of meters, manage cluster resources, perform collision avoidance, and permit cluster reconfiguration.

14) Satellite LAN communications: Inter-satellite communications is required for a dense network of satellites (up to 16 satellites per cluster) at high data rates (on the order of 100 Mbps). Multicast, CDMA, TDMA, FDMA, and other techniques are required for short haul space communications. Protocols that permit high throughput and low data latency are required. Miniature space quality LAN communications hardware will be required.

15) Relative navigation: Techniques and devices are required to provide relative three dimensional position knowledge of the satellites to within 1 cm. These approaches must be adaptable to variable numbers of satellites in the cluster, be space qualified, work in near real time (latency and update times consistent with the orbital drift of satellites out of the cluster formation), and be amenable to lightweight, low cost hardware solutions.

Summary: It is clear that the spacecraft of the future will have to be more affordable and innovative. The Air Force Office of Scientific Research has made significant investments in the basic research methods and space technologies required to enable the future space architects through our university programs. The combined efforts of the Air Force Research Laboratory through the TechSat 21 program will bring a more capable and more cost effective space system to reality. AFOSR is dedicated to the furthering of breakthrough technologies to benefit the US and its allies.

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